JET, NET, DEMO . . .

Europe and nuclear fusion

European File

Commission of the European Communities
Directorate-General for Information,
Communication and Culture
Rue de la Loi 200 — B-1049 Brussels

3/87
February 1987

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The magnitude of the energy problem for Europe and the world can be demonstrated by a few statistics. Each year, the gross internal energy consumption of the European Community is nearly 1 000 million tonnes of oil equivalent (toe). In 1985, the cost of Community imports of energy products exceeded 120 000 million ECU.[1] At world level, it is generally believed that, before the middle of the century, the combined effects of the expected growth of population and the average per capita consumption of energy will lead to a doubling, even a tripling, of world consumption from its current bill of between 6 000 to 7 000 million toe per year.[2]

Between now and the middle of the next century, 80% of world oil reserves are expected to have been exhausted. In these circumstances, an orderly transition to a 'post-oil' society can be ensured only if strategic plans to encourage the use of alternative sources of energy are quickly developed. The exploitation of alternative sources capable of meeting long-term energy needs is all the more urgent because of ecological problems – in particular, acid rain and increased carbon dioxide in the atmosphere – resulting from the use of oil and coal reserves (which remain very substantial). These problems lead us to conclude that after the first decades of the twenty-first century, the use of combustible fossil fuels may gradually have to be abandoned.

Anyone who might be tempted by current petrol prices at the pump to ignore the energy problems of the next century, should be reminded that daily price fluctuations do not alter the underlying trend: unless it can be replaced, a consumable product will become more expensive as it becomes scarcer. We run the risk of learning this lesson fairly quickly when North Sea oil reserves have been exhausted. In any case, with the cost of oil remaining high for the European economy, the best use that could be made of the current breathing space in the oil market would be to encourage the development of long-term alternative sources such as solar energy, fast breeder reactors, and controlled thermonuclear fusion.

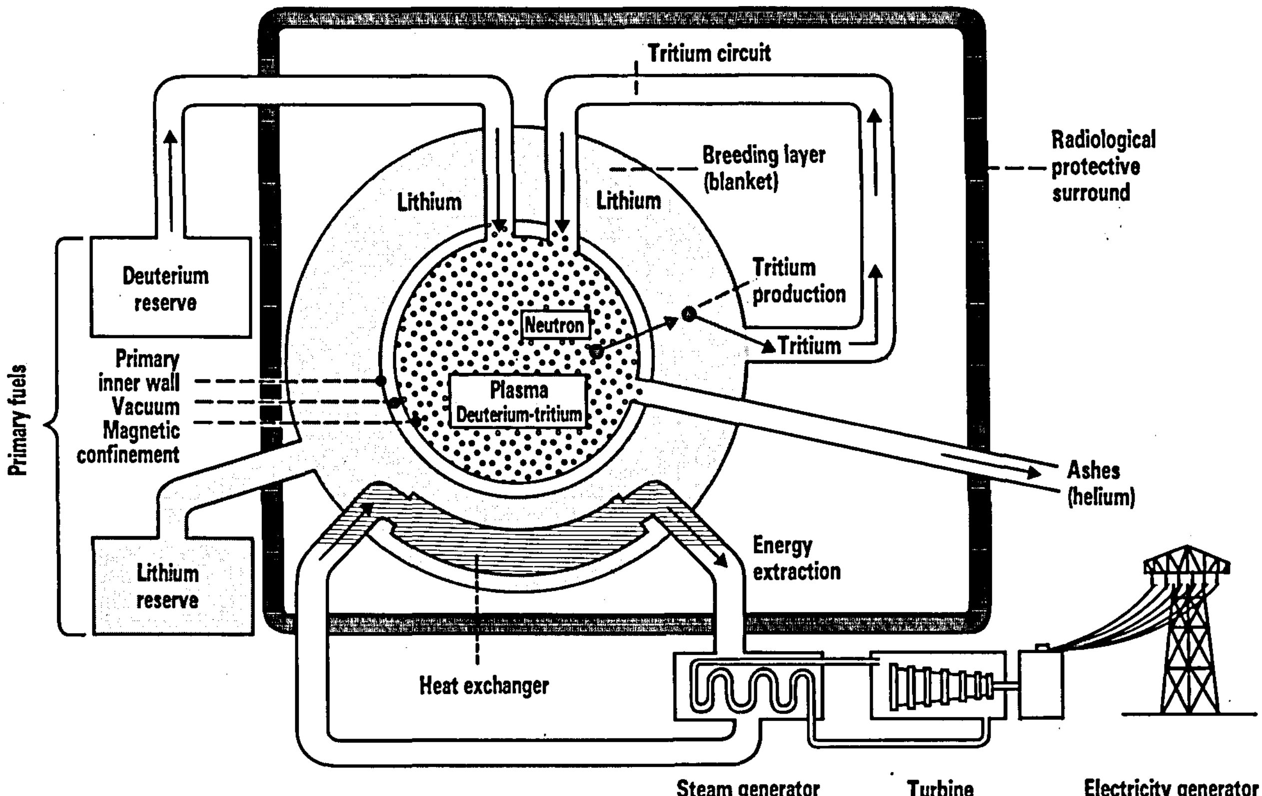
It is not the intention here to analyse the long-term advantages and disadvantages of these various resources, currently being developed in parallel European programmes. Compared to fast breeder reactors, nuclear fusion is only at a preliminary stage of development. Nonetheless, as this document will show, it may be a trump card in the long term.

Nuclear fusion and its problems

All matter is composed of tiny particles, known as atoms. The nucleus of the atom comprises protons, which have a positive electrical charge, and neutrons, which have no electrical charge. Orbiting around this nucleus are electrons, which have a

[1] 1 ECU (European currency unit) – about £0.73, Ir.£0.76 or US $1.07 (at exchange rates current on 8 January 1987).
[2] This file replaces our No 12/82.

Conceptual design of a fusion reactor



Source: Commission of the European Communities, DG XII.

negative charge and which are equal in number to the protons. The binding energy, which fuses the nucleus, varies from one type of atom to another. In certain cases, rearranging the protons and neutrons can unleash a great amount of energy, so-called nuclear energy. Two types of rearrangement are possible: fission, which is used in existing nuclear reactors and which breaks the nucleus, and fusion which on the contrary synthesizes two nuclei into a heavier nucleus and which is equally productive of energy. The fusion of deuterium and tritium — two hydrogen isotopes, the first of which comprises a proton and a neutron and the second a proton and two neutrons — is the least difficult to achieve and therefore will be the first to be exploited in a fusion reactor.

For fusion to take place between two nuclei, they must be propelled against each other with sufficient energy to overcome the repelling forces due to their like electrical charge. When transposed into temperatures, this energy represents an extremely high value, of the order of several hundreds of millions of degrees. At such temperatures, the particles move at extremely high velocity (several thousand kilometres per second). If precautions were not taken, the particles would escape without engendering the collision necessary for a fusion reaction and therefore without producing energy.

Among the solutions being sought to this problem:

- 'Inertial fusion' which consists of creating a medium so dense that a particle has practically no chance of escaping without meeting another. A small sphere formed from a solid mix of deuterium and tritium, suddenly hit by powerful laser light beams, implodes under the shock wave; now several hundred times more dense than in its normal solid state, it explodes under the effect of the fusion reaction.

- 'Magnetic fusion' where an attempt is made to confine the particles in a space limited by a magnetic field. The concept of a material container had to be abandoned — the particles would quickly lose their energy by hitting against the inner walls — so it was decided to exploit one of the properties of plasma. This is a completely ionized gas into which matter transforms itself when heated to very high temperatures which detach the electrons from the nucleus. The essential property is the following: when placed in a magnetic field, the electrically charged particles of the plasma adopt helical trajectories which turn around the lines of force of the field. The result of this is that particles can be trapped for a certain period if the magnetic field is given a torus-shaped configuration (similar to the tyre of a car) where the lines of force close in on themselves. This approach has been selected by the Community. Among the various toroidal magnetic configurations, the 'tokamak' seems today to be the most promising.

As far as can currently be imagined, a fusion reactor would consist of two essential elements (see diagram): an enormous 'burner' containing a plasma of deuterium and tritium, the fusion of which produces helium 'ashes' and highly charged neutrons;

a breeding layer (or blanket), which contains lithium. The blanket is required to produce the necessary tritium which is almost non-existent in nature but which is obtained from lithium when lithium is bombarded by neutrons from the burner. The tritium produced in this manner would be collected and reinjected into the combustion chamber, while conventional heat exchangers would 'pump' the heat from the blanket: this heat would be converted into usable electricity by a steam turbine.

Fusion is the least advanced of all the major new long-term energy sources currently under development, but it offers undisputed theoretical advantages, particularly for Europe:

- Autonomy of supply: the availability of the basic fuels is virtually unlimited, which is a great advantage considering Europe's meagre uranium reserves. Deuterium can be extracted from the ocean (34 grammes from one cubic metre of water) and Europe appears to have sufficiently large reserves of lithium (which can also be extracted from the sea). The amount of energy produced from one gramme of deuterium-tritium mixture equals that produced by burning more than 10 000 litres of oil!

- Operational security and environmental protection: fusion reaction does not in itself produce radioactive waste. Unlike deuterium, lithium and helium, the tritium which serves as fuel is radioactive, but the amount used is minimal. Moreover, because it is produced inside the reactor and used in a closed circuit, no transport is involved. In addition, a nuclear chain reaction is impossible. Even the total destruction of a fusion power station as a result, for example, of an aeroplane crash or an earthquake, would not constitute an ecological disaster. It must, however, be acknowledged that the activation by neutrons of the internal structure of the reactor poses a serious operational problem which must be resolved if the long-term stocking of used components is to be avoided. Great attention is therefore being paid to the development of advanced technologies to resolve or limit this difficulty, which would affect the economic viability of this type of reactor. In the longer term, other fusion reactions might one day replace that of deuterium and tritium; although more difficult to operate, they would generate less radioactivity.

- Contribution to technological progress: the investment devoted to the numerous technological developments required to construct the first fusion reactors will have a wider application than its long-term energy objective. In the near future, technologies thereby perfected will be put to profitable use in other branches of science and industry.

The development of the Community fusion programme

The year 1958 saw the creation of Euratom, the European Atomic Energy Agency, and also a conference, organized in Geneva by the United Nations, which liberated fusion research from the constraints of military secrecy. It became clear at this time that fusion by magnetic confinement would not be as easy to achieve as had initially been thought. In view therefore of fusion's potential advantages for Europe and the enormous practical difficulties of implementation, Community member countries decided to integrate their individual national efforts into a single European programme which would support and coordinate the activities of all the specialized laboratories located in Member States. Since then, these laboratories have been bound to the Community by contracts of association which provide for Euratom participation in personnel and financing. The European Commission has full executive responsibility for the programme and is assisted by a consultative committee on the fusion programme, composed of national experts. In addition, a joint undertaking has been established for the JET project; it is administered by the JET Council and a project director. The collective nature of this project and its remarkable team spirit are testified to by several decisions of the Community's Council of Ministers. These describe the Community fusion programme as 'a part of a long-term cooperative project embracing all the work undertaken in the field of controlled thermonuclear fusion in the Member States. It is designed to lead in due course to the joint construction of prototypes with a view to industrial-scale production and marketing'. Such an undertaking is without precedent in the history of international scientific cooperation.

The evolution of the European programme, from one decade to the next, may be schematized as follows:

☐ In the 1960s, priority was accorded to the problems of magnetic confinement and, to a lesser degree, the heating of plasma. The European Commission paid particular attention to avoiding unnecessary duplication and encouraging information exchanges. However, the dimension of the problem changed after the first successes of a Soviet tokamak; Europe had to catch up on, and do better than, the USSR. To encourage the work of national laboratories, the Community raised its financial support from the usual level of 25% to nearly 45% for capital investment for the construction of major experimental plants of joint interest.

☐ The 1970s were characterized by the construction of several machines of the tokamak type. The design and start of construction of JET (Joint European Torus) was the climax of this period. JET was the first project proposed in the world for a major experimental machine in the fusion field. Its realization was the result of joint efforts by national laboratories and the Community, which covered 80% of the costs.

☐ The 1980s have so far been marked by scientific and technical developments which place the European programme in the first rank of world fusion research.

The Community fusion programme has demonstrated its effectiveness. Starting from national laboratories, large and small, a veritable scientific and technical community has been built up in the common interest. Its 'mobility' budget has given a vigorous impetus to scientific exchanges between the various European laboratories. In addition, the participation of Sweden and Switzerland, two non-member countries, is another sign of the success of a programme which is open to new partners and to the integration of their activities in the pursuit of a common aim. Fusion is the only scientific area in which there is full integration at the European level; its programme structure and content make it a model for other European activities in the science and technology field.

Objectives and content of the European programme

The developmental path towards a fusion reactor able to produce energy can be divided, albeit arbitrarily, into three sections: demonstration of the scientific feasibility of a fusion reactor, of its technological feasibility and — eventually — of its economic feasibility. With the JET, medium-sized tokamaks and their foreign equivalents, we are still at the stage of scientific feasibility. However, it is now considered that the successor to JET, the NET (Next European Torus), which is at the preliminary project stage, should fully confirm the scientific feasibility and should also tackle the problems of technological feasibility.

The current objectives of the fusion programme are:

- ☐ To establish the physical and technological base necessary for the detailed design of NET. To do so, full use must be made of JET and other specialized medium-sized tokamaks. A strengthening of the technological side of the programme is also needed.

- ☐ To undertake, probably in 1989-90, the detailed design of NET.

- ☐ To explore the potential of certain alternative tokamak configurations (stellarators and reversed field pinches).

Impressive results have already been achieved with European machines. Two examples are given below:

- ☐ Located at Culham in the United Kingdom, JET represents the most advanced fusion experiment in the world. Following the installation of powerful supplementary heating systems, plasma temperature was recently raised to more than 100 million degrees. To improve even further on this performance, it seems that it will be necessary to reinforce the machine.

- ☐ A new way of confining plasma, obtained in the Asdex tokamak located at Garching in Germany, has confirmed that it is possible to suppress, or at least limit, certain effects of heating plasma that shorten the duration of confinement.

Several other machines have been equipped with powerful plasma heating systems, while others are under construction. Four of these machines, located at Cadarache

(France), Garching (Germany), Frascati (Italy) and Culham (United Kingdom), are of the tokamak type. In addition, a new stellarator is being constructed at Garching as well as a reversed field pinch at Padua (Italy).

Parallel with experiments in plasma physics, a major programme to develop the technologies required for NET and, in the longer term, for a fusion reactor, has been started in the following fields:

- Superconducting magnets for the creation of 'continuous' magnetic fields.
- Components for a tritium recovery system.
- Blanket technology (two types of lithium compounds for the production of tritium are being examined).
- Materials for the reactor structure, its primary inner wall, thermal insulation, etc.
- Safety and the environment: prevention of the possible escape of tritium in gaseous form and treatment of the used reactor components contaminated by tritium.

The Community's Joint Research Centre actively participates in work related to tritium technology, materials and security.

In addition, the contribution made by European industry was a determining factor in the successful construction of JET and other experimental machines.

A new Community fusion programme is being prepared; it will run for a five-year period (1987-91). The proposal for a second framework programme for Community technological research and development, submitted by the European Commission to the Council of Ministers, foresees an allocation of 1 100 million ECU for fusion over five years.

Future prospects

The ultimate goal of the Community fusion programme is the construction of a demonstration reactor, DEMO, able to produce electricity in a satisfactory manner. DEMO should also serve as a model for the use of tritium in optimal conditions of safety and reliability. Between JET, which is concerned solely with scientific demonstration, and DEMO, there is clearly much ground to be covered. Nevertheless, it is hoped, and generally considered feasible, to cover this distance in one step through NET, which is the new medium-term objective of the European programme. NET should be an intermediate machine provided with all the components derived from the first generation of fusion reactor. While NET will certainly be a tokamak, the choice of the basic design for DEMO remains open. However, it is considered that the required technological developments are more or less common to all toroidal confinement configurations.

As happened with JET some 12 years ago, a study group has been established to define NET specifications. The group is based at Garching. The experience and results gained from the operation of JET and medium-sized machines already installed or under construction, together with anticipated technological progress, make it probable that the NET project can start in a few years from now. Other anticipated scientific and technological progress should enable construction to begin during the first half of the coming decade. However, it is all the more difficult to forecast at this stage because it is not certain whether NET will remain a purely European undertaking. There are certain indications today that, due in particular to the high cost of this intermediary stage, the machine may be constructed as part of a broader, perhaps world-wide, cooperative effort.

Progress in international cooperation

The availability of fusion energy could be of considerable advantage to all mankind, exceeding by far the benefits and prestige which any one country might gain from perfecting a single fusion reactor. In any event, a rapid dissemination of the new technology can be expected, making it available to all. If every country with the necessary scientific and technical resources has to participate in fusion research, such research would clearly gain from being undertaken in a spirit of cooperation rather than of competition. Coordination of efforts would enable the goal to be attained more easily, more rapidly and more economically.

At the moment, there are four fusion programmes which are more or less equivalent: in the Community, the USSR, the United States and Japan. The scale of these programmes, their achievements and their goals are comparable. The Community fusion programme is, however, the first supranational attempt which has made a major contribution to scientific and technical progress. As it stands today, the programme structure and content make Europe an attractive partner in international cooperation.

Several agreements have already been signed un the aegis of the International Energy Agency of the OECD, the organization which groups industrialized countries with free market economies. Agreements have been concluded by the Community, and more specifically by Euratom, on behalf of all countries participating in the European programme. These agreements join together:

- ☐ The Community, the United States, Canada, Switzerland and Turkey to study the interaction between plasma and the tokamak chamber (this work is being carried out at the Textor tokamak at Jülich in Germany).
- ☐ The Community, the United States, Japan and Switzerland to develop superconducting magnetic coils.

- ☐ The Community and the United States in research on torus physics and plasma technology, applicable to certain types of tokamak and also to the development of certain alternative configurations: stellarators and reversed field pinches.

- ☐ The Community, the United States and Japan for cooperation among their three principal tokamaks, including the JET.

The Community will soon be linked to most of its major partners by general bilateral agreements. Such agreements have already been signed with Canada and the United States, while an agreement with Japan is under preparation. Furthermore, the Community participates in Intor, the working group of the International Atomic Energy Agency, as do the three other major fusion powers, including the USSR. By virtue of measures agreed at the Summit of Western powers, held at Versailles in 1982, the European Commission plays a key role, with the American Government, in strengthening international cooperation in the fusion field.

Following the 1985 American-Soviet Summit in Geneva, one cannot rule out cooperation at world level measuring up to the high cost of NET and the complexity of the equipment needed. The overtures made in this direction by Mr Reagan and Mr Gorbachev were received with interest by world fusion specialists and Western authorities are actively studying in detail the feasibility of such an undertaking.

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Physicists assume and hope that nature allows plasma to be confined for the necessary length of time while it is maintained at temperatures exceeding 100 million degrees, but they still have to find simple means of establishing such conditions. In addition, engineers still have the task of developing advanced technologies which would allow wide-scale exploitation of these conditions in a reliable and efficient manner.

The hope is that physical problems will be resolved by studying the current generation of machines, and in particular, the JET, so that the next step, the construction of an experimental fusion reactor, may begin, if necessary in a framework of major international cooperation.

As regards the ecological aspects of fusion, the future appears equally favourable, as indicated in a report prepared for the European Parliament. The principal advantages to be underlined are the minimal consequences of a serious accident and the lack of any important long-term risk ■

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Office for Official Publications
of the European Communities
L - 2985 Luxembourg

ISSN 0379-3133

Catalogue number : CC-AD-87-003-EN-C